NSTX Supported by U.S. DEPARTMENT OF ENERGY | Office of Science

Overview of NSTX Liquid Lithium Divertor Performance and Divertor Upgrade Plans

College W&M
Colorado Sch Mines
Columbia U
CompX
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin

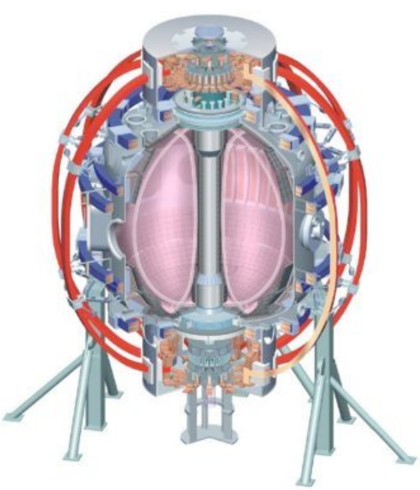
R. Kaita

Princeton Plasma Physics Laboratory

53rd Annual Meeting of the American Physical Society
Division of Plasma Physics

Salt Lake City, UT

November 14 - 18, 2011



Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

Coauthors and Acknowledgements*

H. W. Kugel 1), M. G. Bell 1), R. Bell 1), A. Diallo 1), S. Gerhardt 1), M. Jaworski 1), J. Kallman 1), S. Kaye 1), B. LeBlanc 1), D. Mansfield 1), J. Menard 1), D. Mueller 1), S. Paul 1), A. L. Roquemore 1), F. Scotti 1), C. H. Skinner 1), L. Zakharov 1), J. P. Allain 2), A. McLean 3), R. Maingi 3), R. Nygren 4), R. Raman 5), S. Sabbagh 6), and V. Soukhanovskii 7)

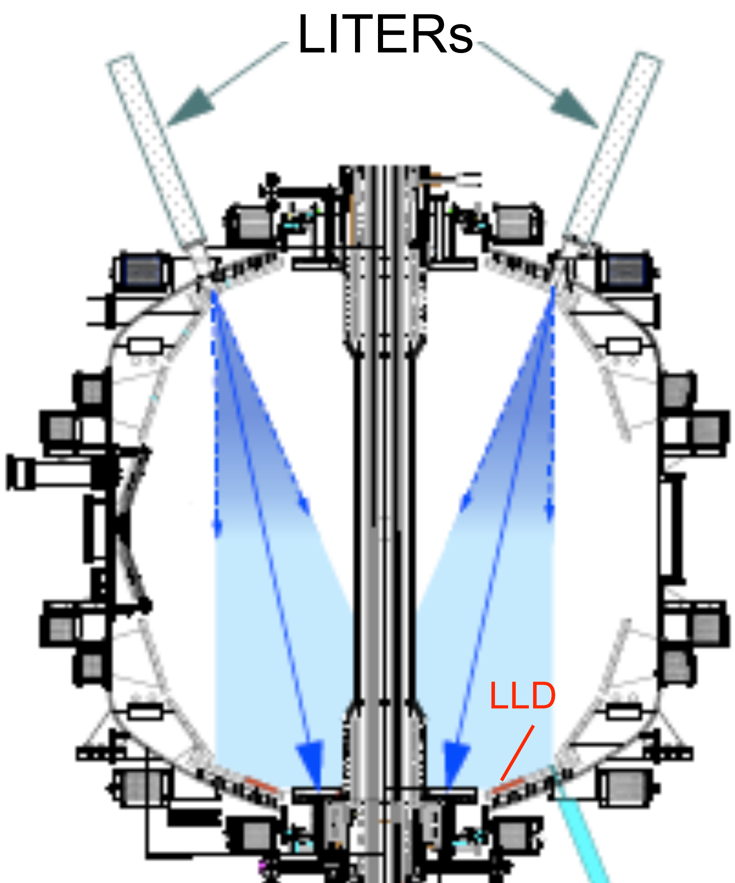
1) Princeton Plasma Physics Laboratory, Princeton, NJ 08543
2) Purdue University, School of Nuclear Engineering, West Lafayette, IN 47897
3) Oak Ridge National Laboratory, Oak Ridge, TN 37831 USA
4) Sandia National Laboratories, Albuquerque, NM 87185 USA
5) University of Washington, Seattle, WA 98195 USA
6) Columbia University, New York, NY 10027 USA
7) Lawrence Livermore National Laboratory, Livermore, CA 94551 USA

*Work supported in part by US DOE Contracts DE-AC02-09CH11466, DE-AC05-00OR22725, DE-AC52-07NA27344, and DE-FG02-08ER54990

Abstract

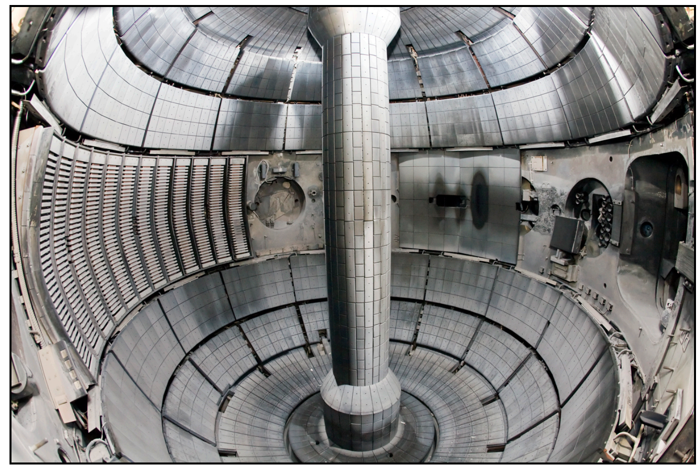
NSTX experiments were conducted in 2010 with a Liquid Lithium Divertor (LLD) surface that covered the outer part of the lower divertor. It was designed to study the deuterium retention properties of a static liquid lithium surface, refreshed by lithium from evaporators to approximate a surface renewed by flowing liquid lithium. The LLD surface temperature ranged from below to above the lithium melting point, depending on the amount of applied and plasma heating. Noteworthy improvements in plasma edge conditions were obtained, and analysis is in progress to compare them with previous lithiated graphite results. Following the end of 2010 plasma operations, repairs were made to the mechanical damage, apparently from plasma current disruptions, to the LLD supports and other hardware, and the LLD was reinstalled. A row of molybdenum tiles was also installed inboard of the LLD. Since the LLD substrate is porous molybdenum, experiments with both inner and outer strike points on lithiated molybdenum will be possible in 2011-12.

Dual lithium evaporators used to deposit lithium coatings on NSTX lower divertor since 2008



LITERs aimed toward the graphite divertor. Shown are
1/e widths of the emitted gaussian-like distribution.

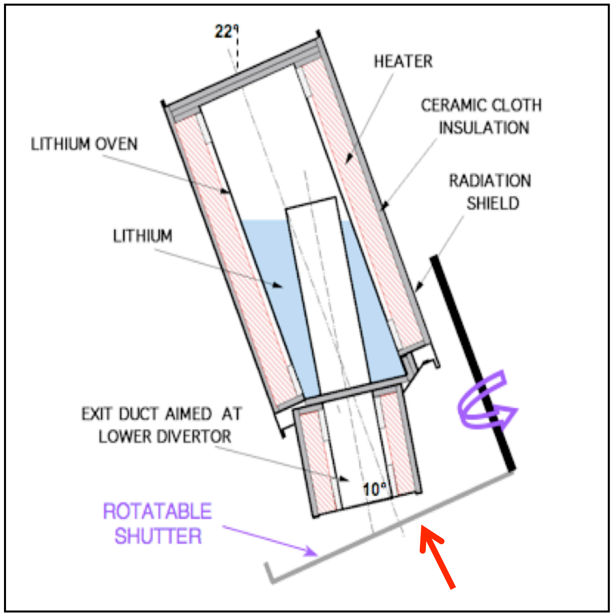
Lithium evaporated for 10 minutes between discharges for about 80% of plasmas
- Transported over broad area by wings of LITER distribution and plasma migration.



2009 Photo: After exposure to air, 600g Li deposition converts to white lithium carbonate (Li_2CO_3)
- Li_2CO_3 removed prior to evacuation with 5% solution of acetic acid to convert Li_2CO_3 to water soluble lithium acetate

Enabling technologies developed to support NSTX lithium deposition

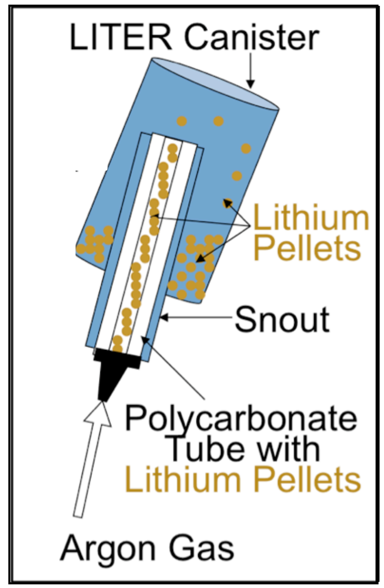
LITER Oven on 1.6m Probe



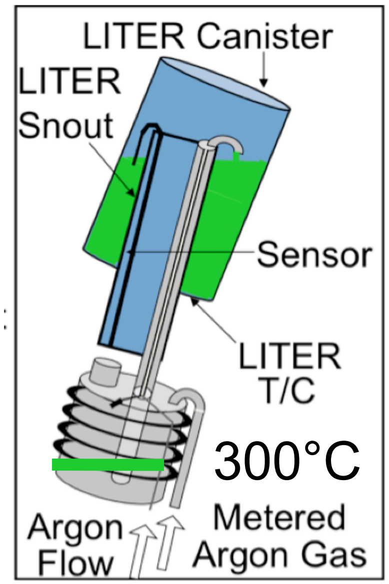
- Rotatable shutter stops lithium when diagnostic window shutters open.

- 4 LITER Units:
  - 2 mounted on vessel
  - 2 for reloading
  - replaced every~2 wks.

Initially, LITERs filled using solid Li pellets injected with Ar (40g max).



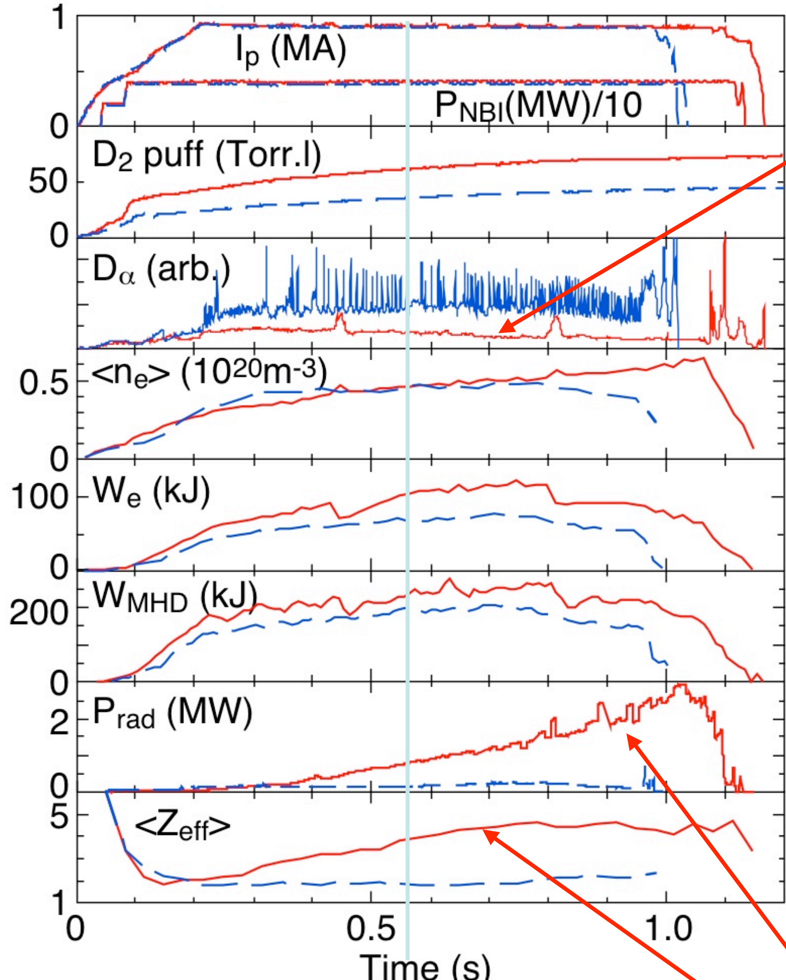
In 2010, LITERs filled using liquid lithium injected with Ar (80g max), less impurities.

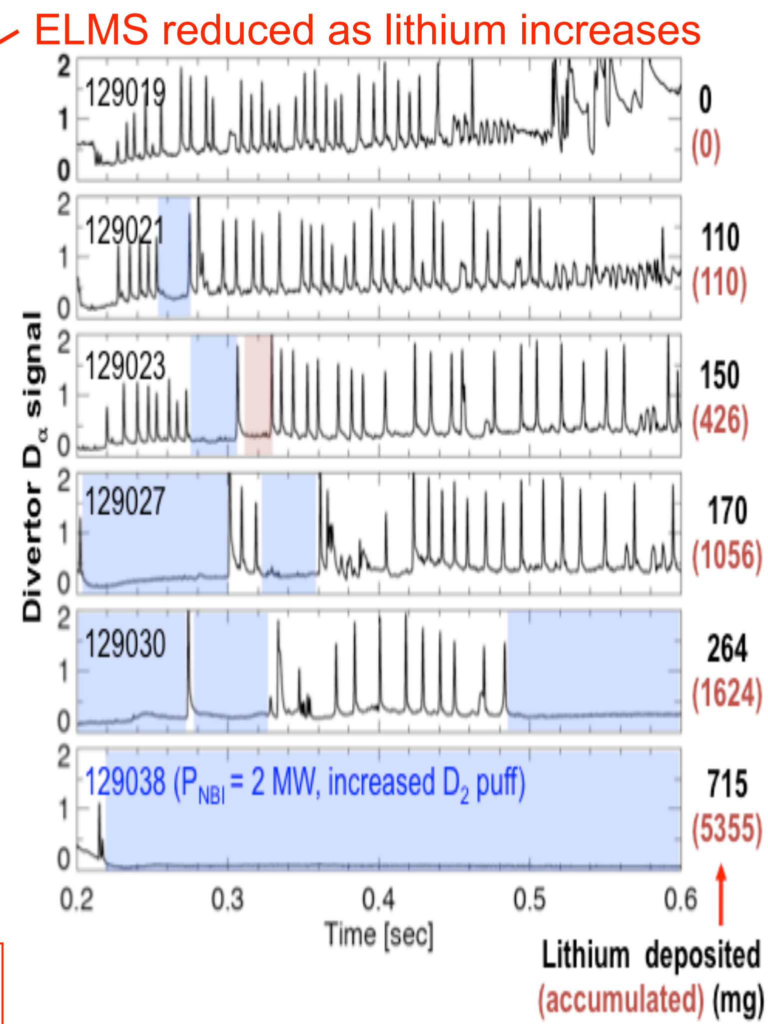


After Li filling, prior to installation on NSTX, LITERs are outgassed in vacuum to 600°C to remove any argon and dissolved gases.

Solid lithium coating on carbon tiles reduces D-recycling and H-mode power threshold, broadens electron temperature profiles, decreases electron thermal diffusivity, suppresses elms, and improves confinement

- No lithium (129239); 260mg lithium (129245)





Without ELMs, impurity accumulation increases radiated power and Z_{eff}

Need to renew solid lithium coatings between discharges motivates liquid lithium plasma-facing surface development

Evaporative lithium coatings incompatible with long pulse, high power divertor operation

Flowing liquid lithium provides a scheme for avoiding limitations of evaporative lithium coatings (erosion, evaporation, saturation…). 2010 implementation of Liquid Lithium Divertor (LLD) designed to test two key issues:

- Substrate compatible with liquid lithium and able to withstand high heat loads
- Performance of static liquid lithium relative to flowing liquid lithium

LLD operation successfully demonstrated with the divertor strike points on lithium-filled surface

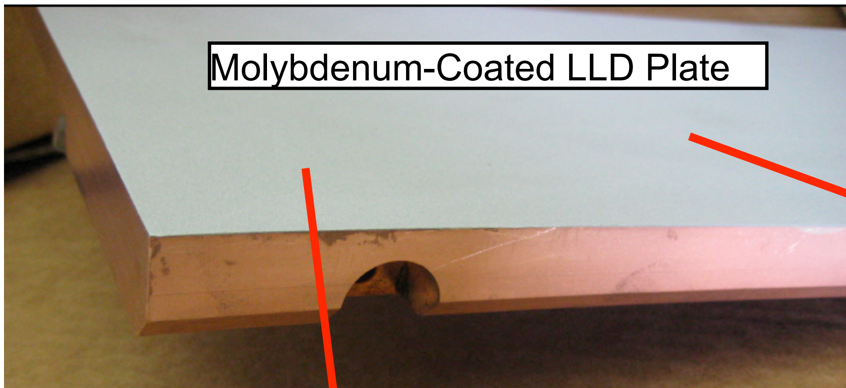
- Design incorporated plasma-sprayed molybdenum surface, on thin stainless steel liner, brazed to thick copper baseplate
- Thermal response during discharge dominated by thermal mass of the copper
- No macroscopic evidence of surface damage by lithium or heating

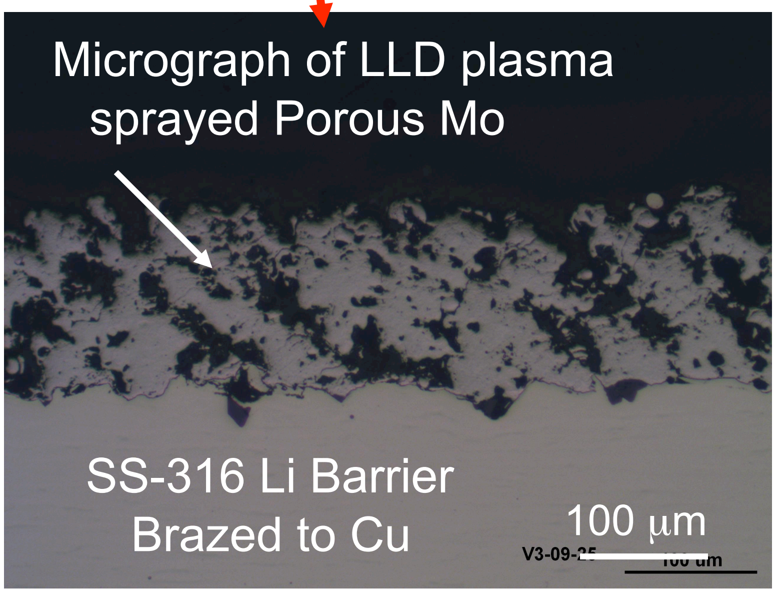
LLD in its effects on plasma performance did not clearly differ from those of evaporative lithium coatings

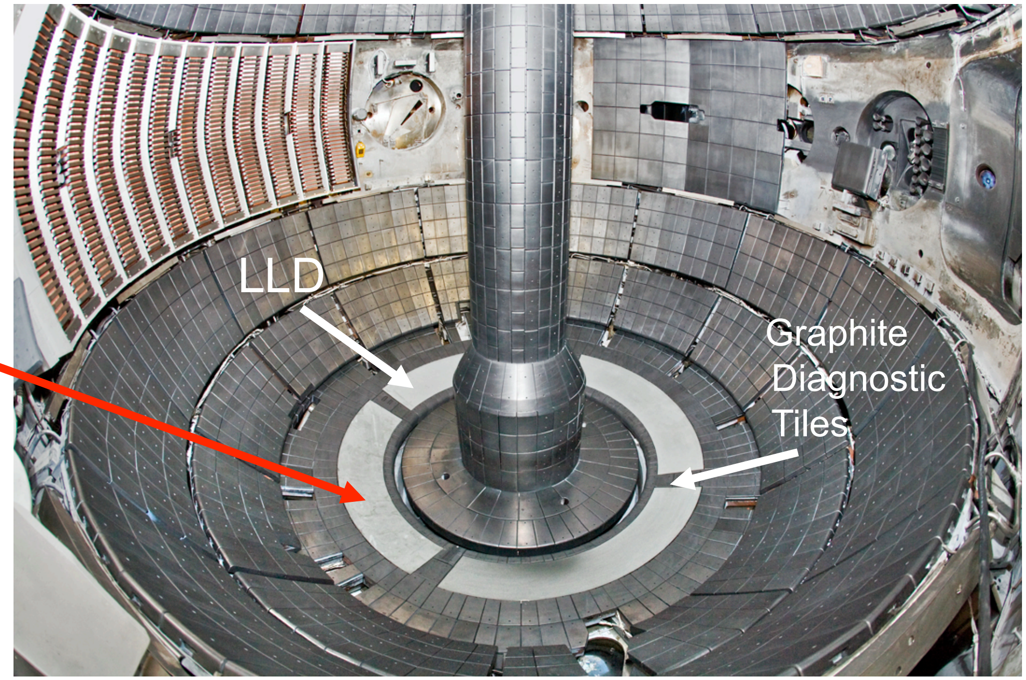
- LLD temperatures exceeded melting point of lithium
- Lithium compounds from impurities remain undissolved on surface

Liquid Lithium Divertor (LLD) installed in 2010 in NSTX with porous molybdenum plasma-facing surface

0.165 mm Mo plasma sprayed with 45% porosity on a 0.25 mm SS barrier brazed to 22.2 mm Cu.



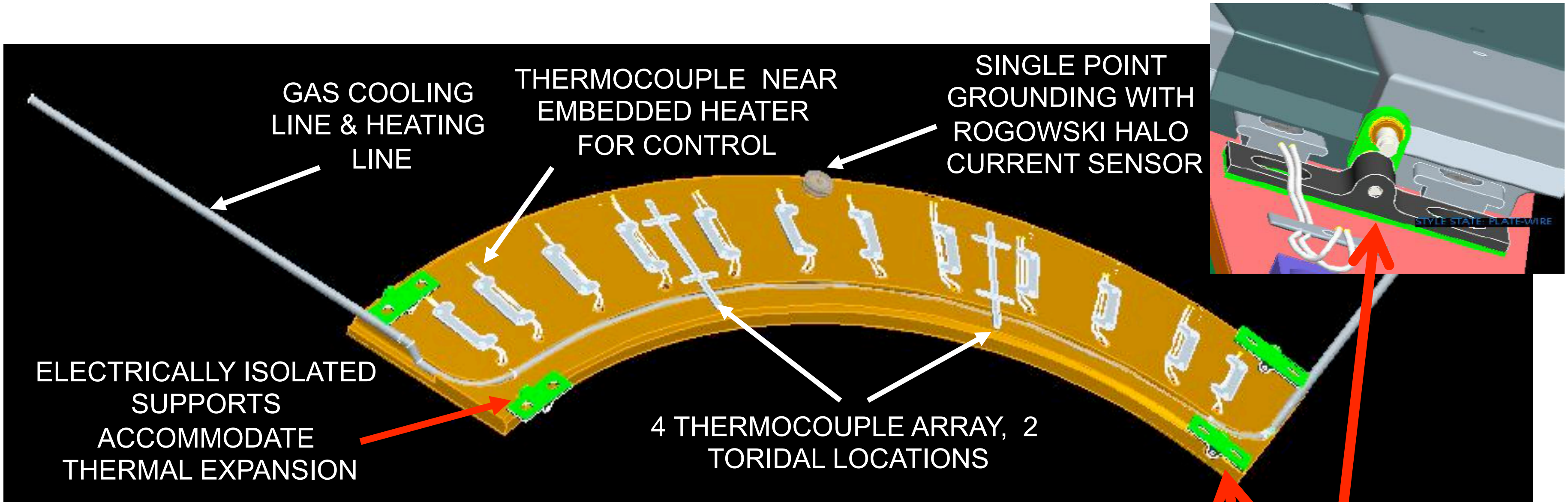




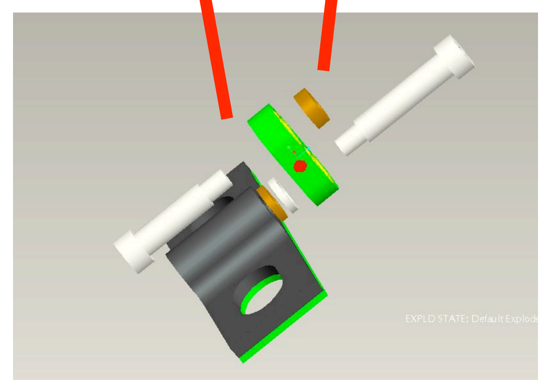
4 heated plates (80°each) separated by graphite diagnostic tiles. Each section electrically grounded at one location to control disruption induced currents

- LLD loaded by LITER evaporation
  - 5% of LITER output reaches LLD
  - LLD has 37g Li capacity (100% full)
  - 2010 tests with LLD up to 200% full

Underside of LLD copper substrate with heating and cooling components, thermocouples, and induced current sensor

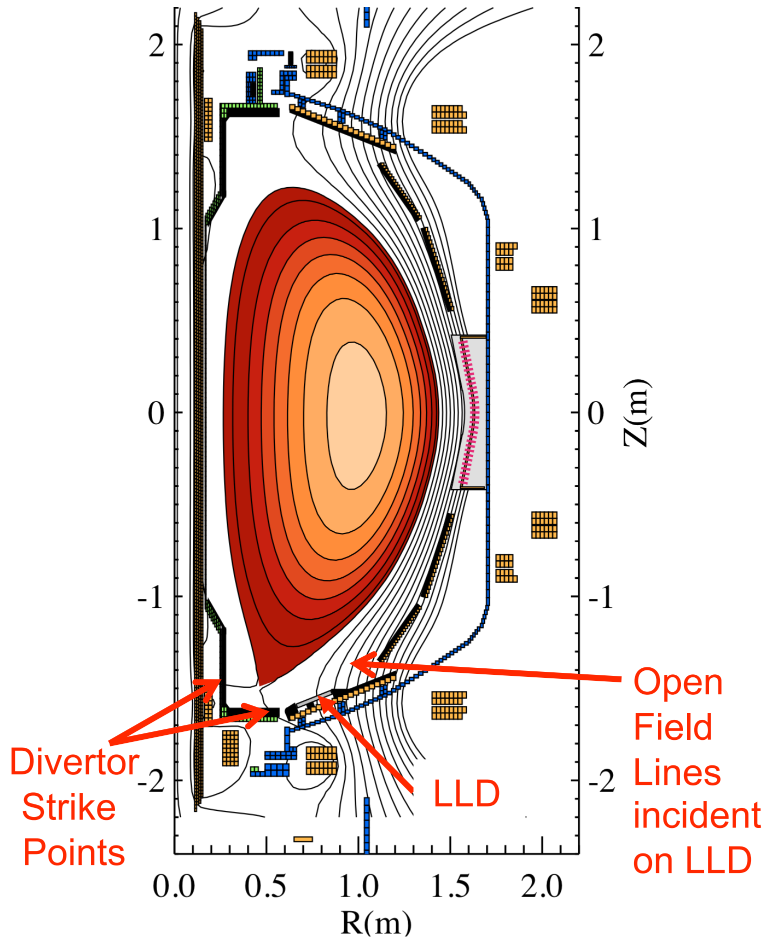


- 12 heaters (240v) each with embedded TC for monitoring heater limits.
- 12 TC embedded in copper baseplate for monitoring heat transfer.
- 2 strips of 4 TC each for monitoring torodial and radial temperature variations.
- 1 Center post Rogowski coil for monitoring currents during disruptions of the plasma current.
- Dedicated computer control system.

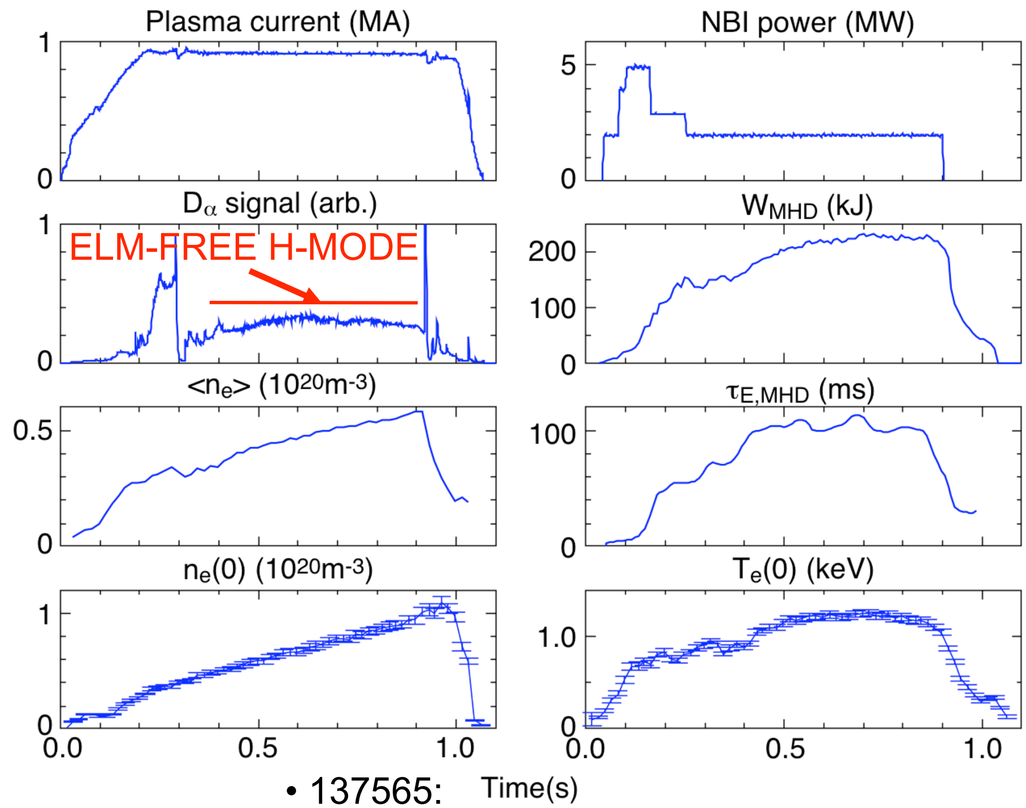


- Mechanical Support
- Thermal Isolation
- Electrical Isolation

Initial results with modest lithium deposition and open field lines on LLD yielded divertor discharges similar to lithiated graphite in performance



TYPICAL DISCHARGE OBTAINED WITH LITHIUM WALL CONDITIONS



- 137565:
  - OSP=0.50m on graphite with open field lines on LLD with Li fill <5%
  - LLD T_0 = 319°C, LITER 21mg/min

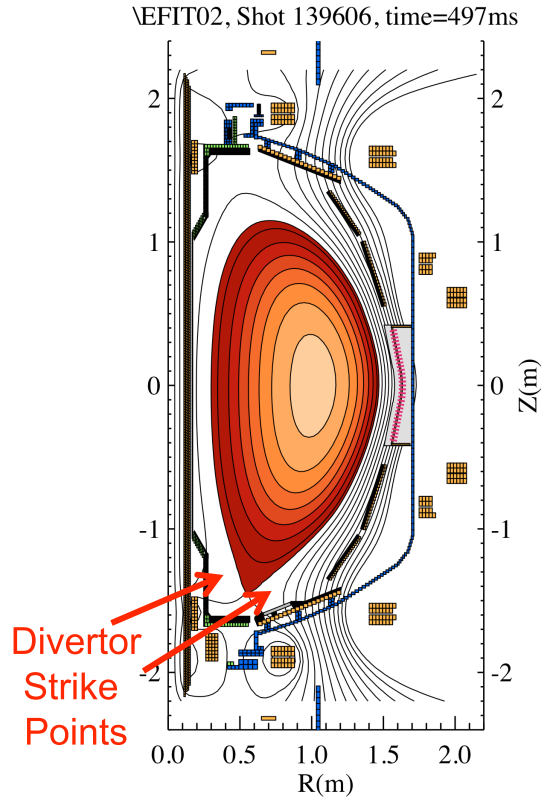
The required fueling and resultant edge conditions were about the same as when using lithiated graphite over entire lower divertor

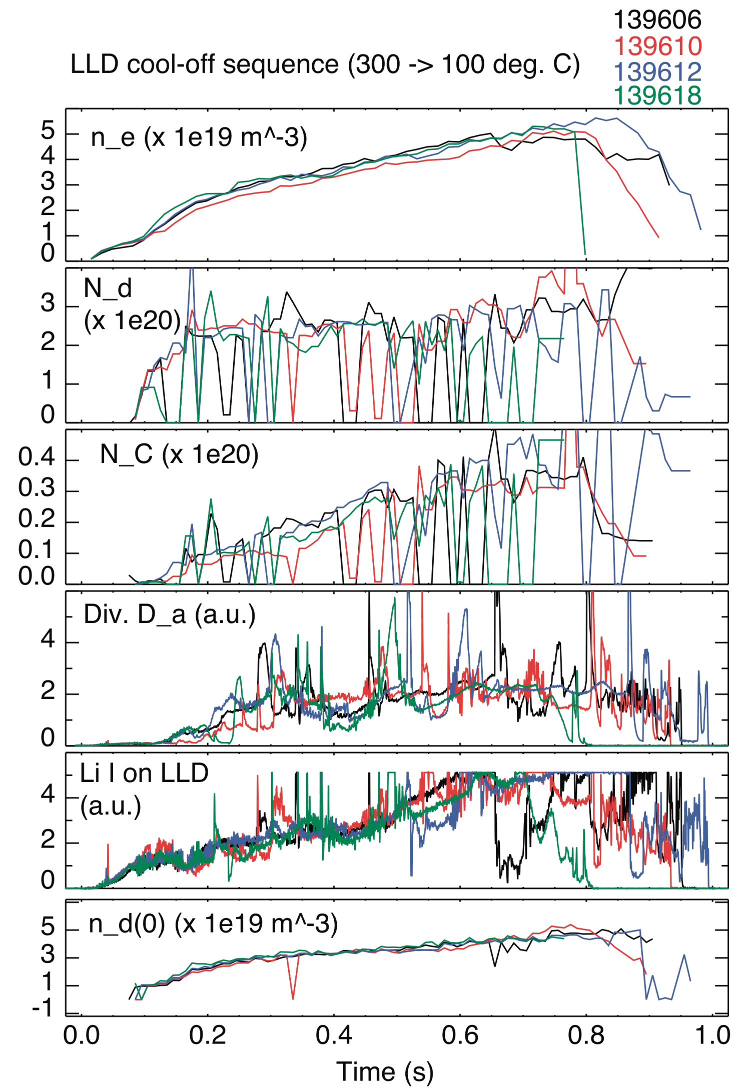
Plasmas with strikepoint on LLD after higher Li evaporation needed fueling comparable to lithiated graphite discharges

<u>Diverted operation</u>

<u>LLD did not require more fueling.</u>

- Deuteron core densities and inventories similar regardless of LLD T(°C)
- Core carbon inventories similar to regular LITER discharges
- Less quiescent edge (from D_α measurements)



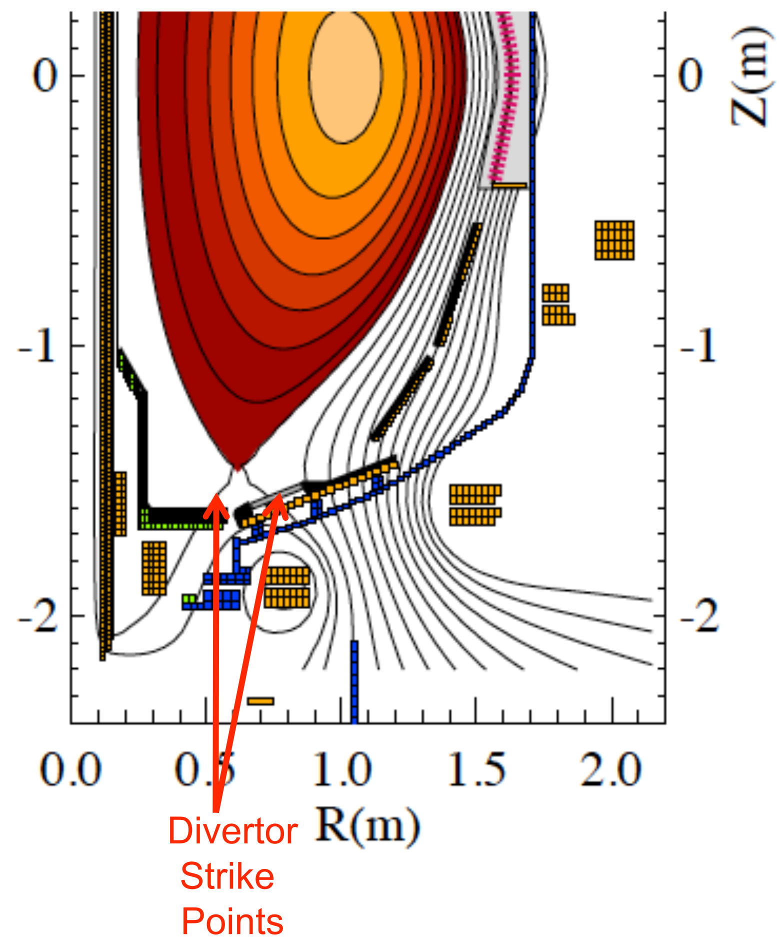


75 hours of lithium evaporation deposited 260 g on lower divertor

Li deposited sufficiently fast to allow 30 discharges on the LLD and then 150 discharges on lithiated graphite without needing He GDC between discharges

LITER evaporation provided sufficient Li deposition to exceed volume of porous Mo LLD surface by end of 2010

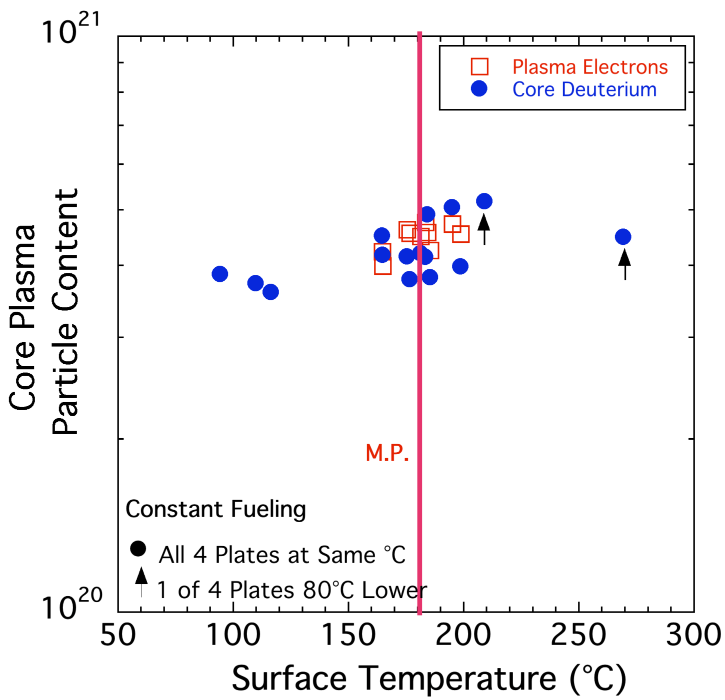
- Discharge
  - I_p = 0.8MA,
  - P_{NB} = 4.0MW
  - B_T = 0.48T
  - R_{OSP} = 0.78m

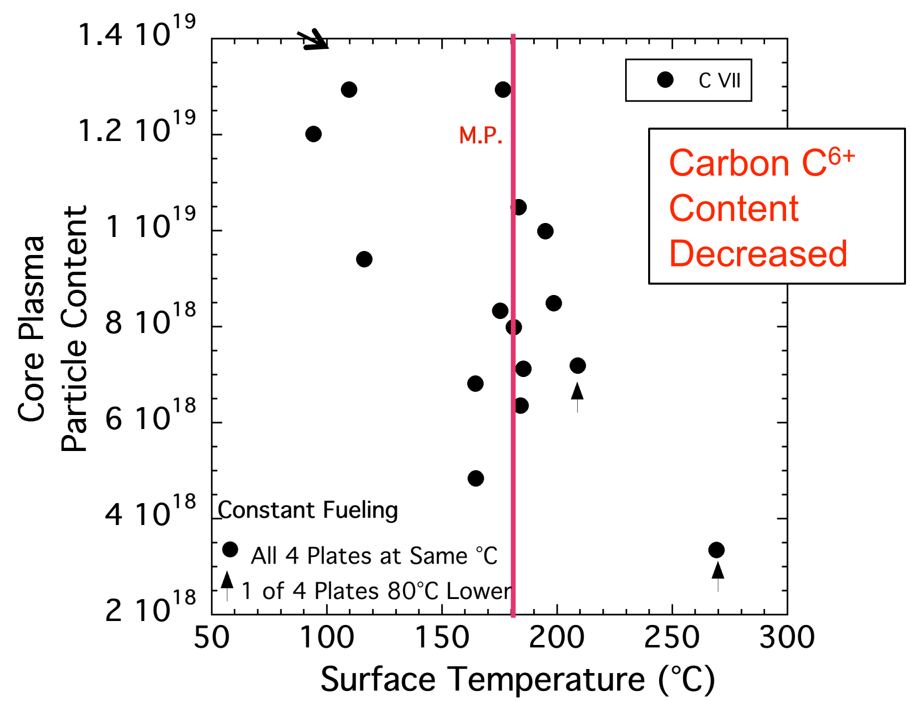


- LLD Lithium Content
  - LLD fill ~200% (67g)
  - Sequence preceded by 7g LITER deposition.
  - No LITER between discharges

Core electron density and core D remained relatively constant but core C^{6+} decreased as LLD surface temperature exceeded Li melting point

- Same fueling for each plasma
  - no additional fueling required to maintain reference discharges

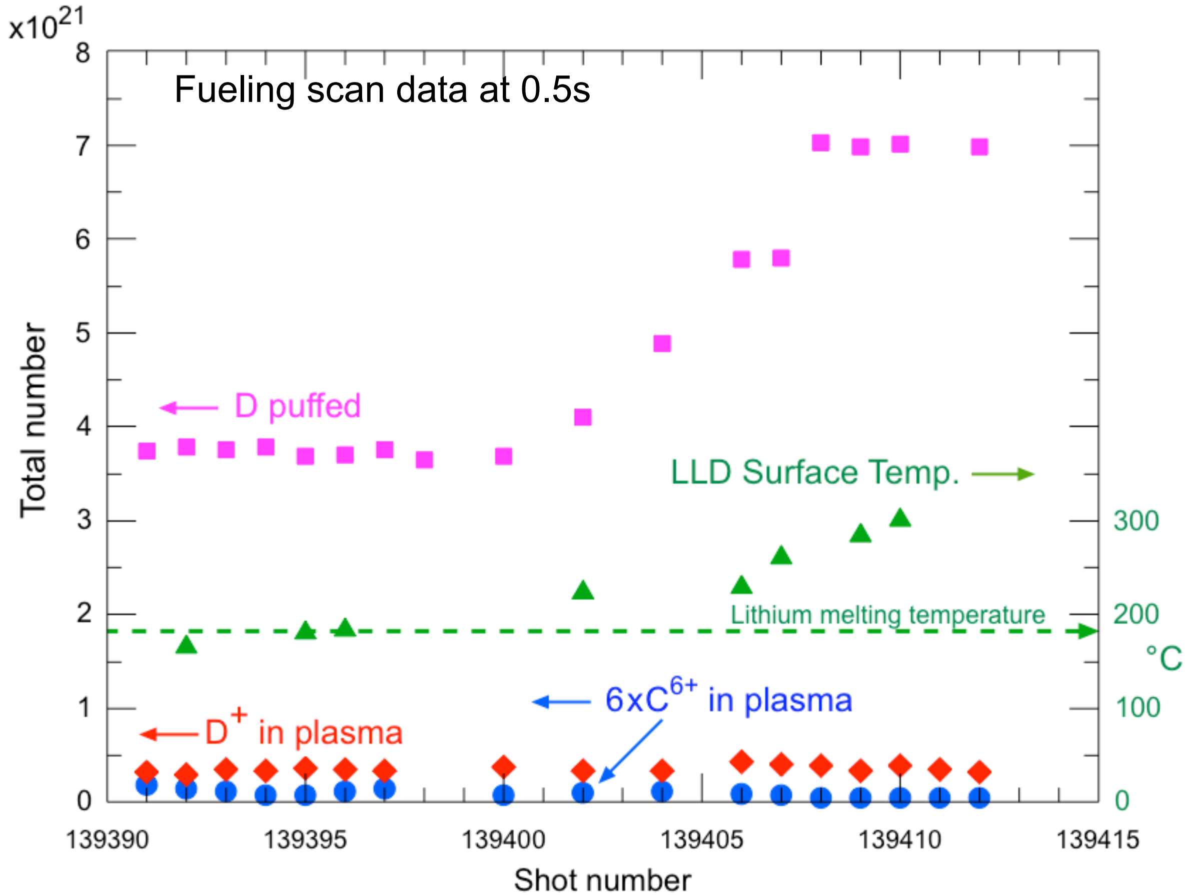




- Indicates that D absorption at solid and liquid lithium temperatures was same
- The decrease in core carbon as temperature increased was coincident with increasing ELMs (need to do reverse experiment, i.e., from liquid to solid)

No change in deuterium content in plasma with increased fueling

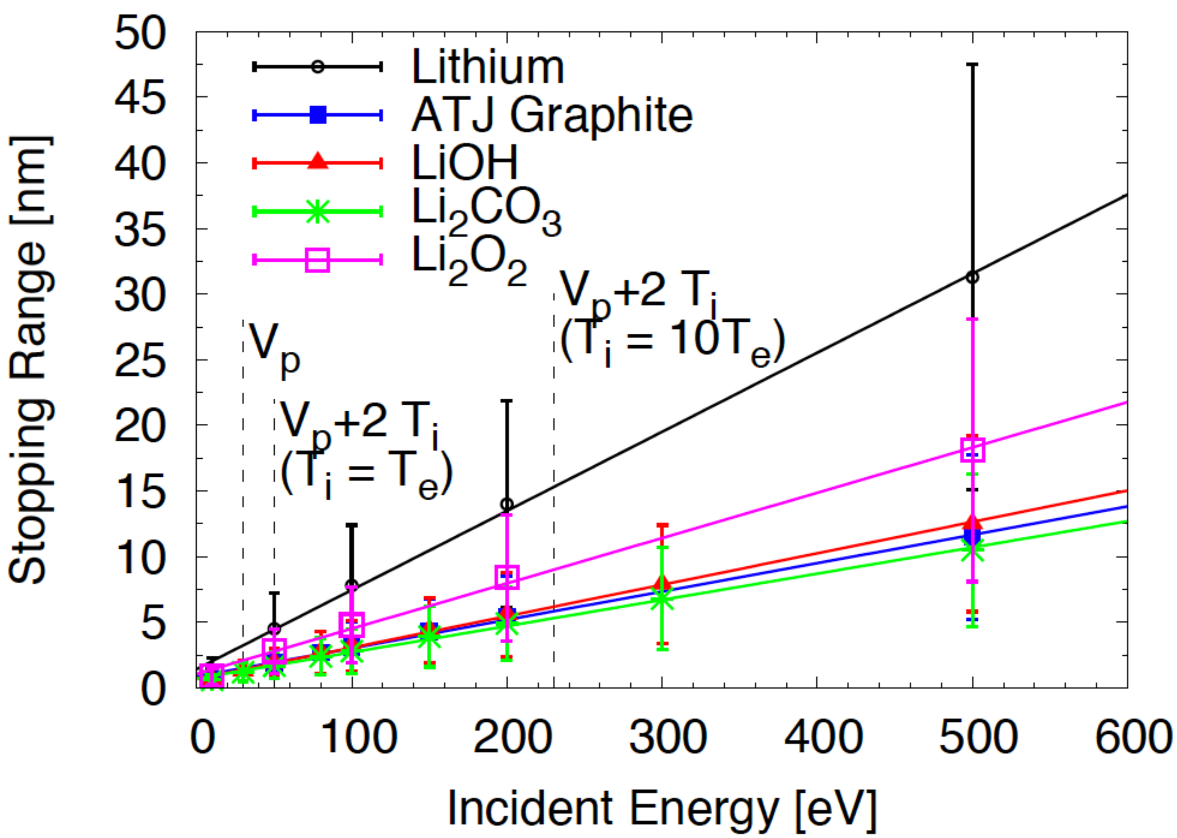
Total number of D particles puffed (gas fueling), and the resultant D and C^{6+} plasma content versus LLD surface temperature during the plasma.



Need to investigate if the added D, after becoming ionized in the SOL open field-lines, flowed to the divertor, and was absorbed by the liquid lithium rather than increasing the plasma density.

D stopped by Li compounds on LLD surface may explain similarity with solid Li coatings on carbon

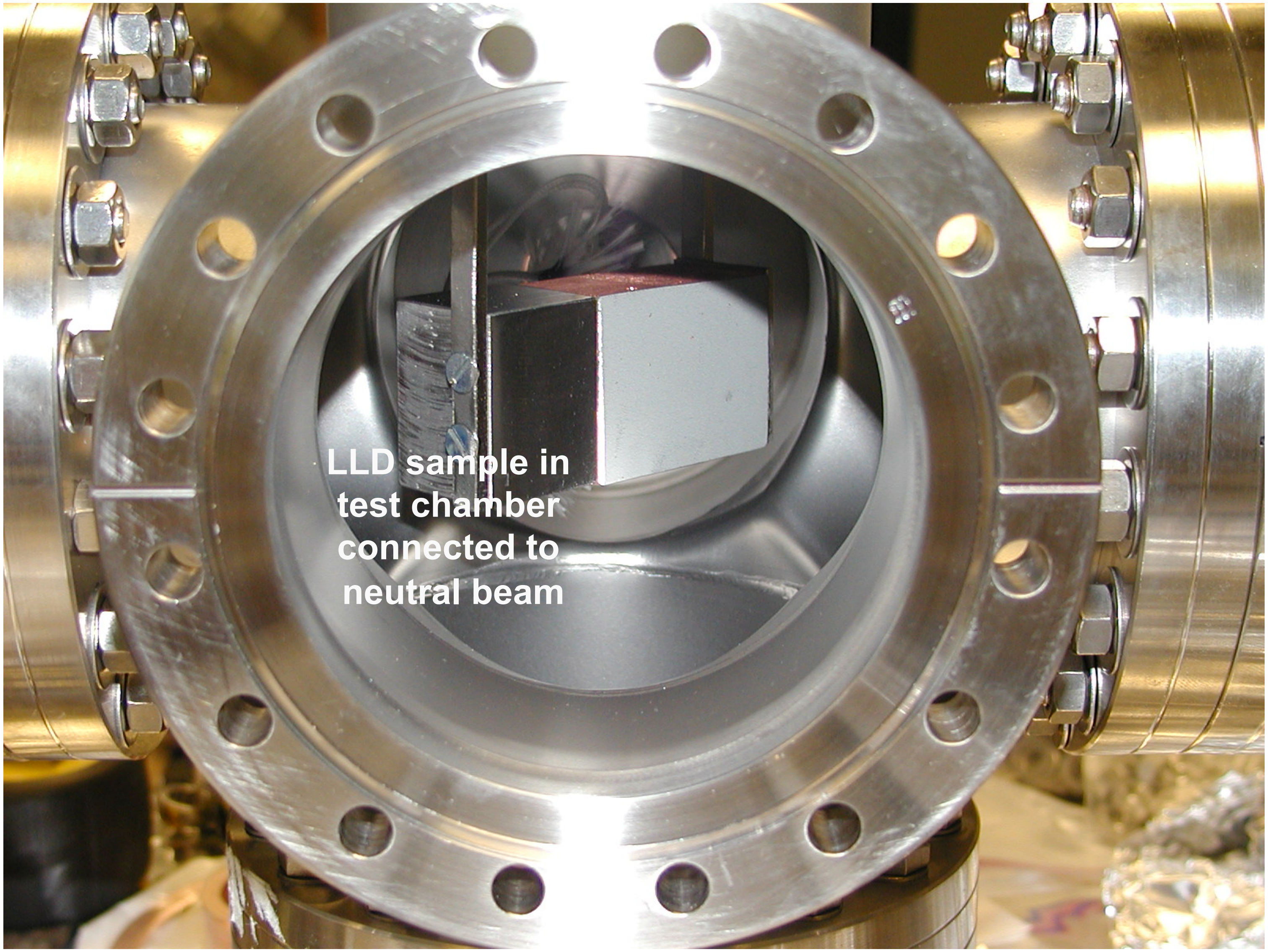
- Static liquid lithium on LLD, getters NSTX Vacuum partial pressures (H_2O, CO, CO_2)
- Divertor LP array (NSTX/UIUC) and midplane CHERS indicate D ion energies of ~50eV incident on the resulting LLD surface of lithium impurity compounds



Reference TRIM Stopping Range Calculation - M. Jaworski

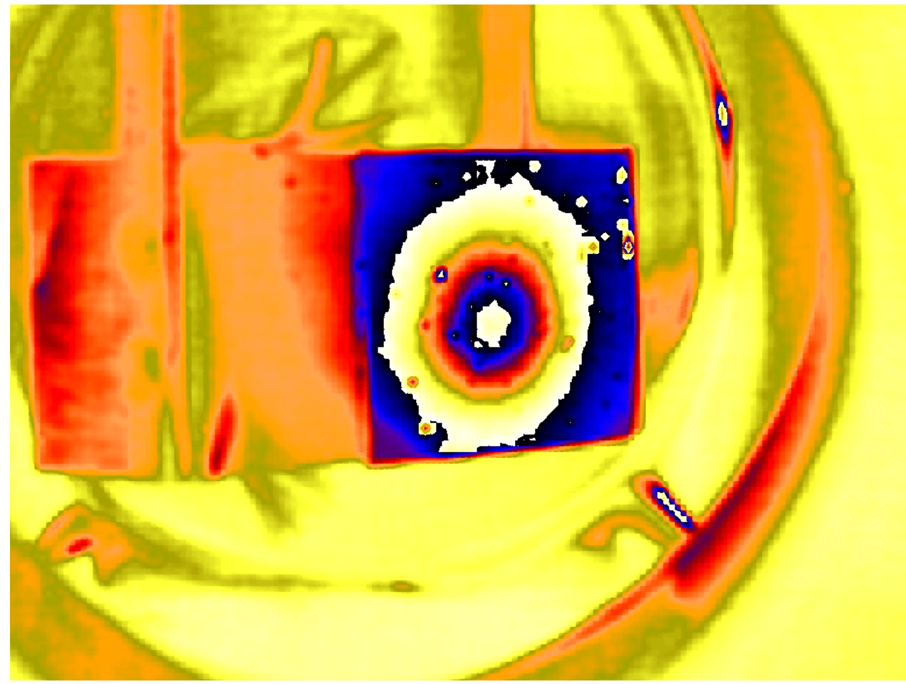
- Work is in progress to investigate if D-Li-O-C complexes on lithiated graphite and static liquid lithium surfaces exhibit similar D retention.

LLD behavior with surface temperature above and below Li melting point motivated study with high-power neutral beam



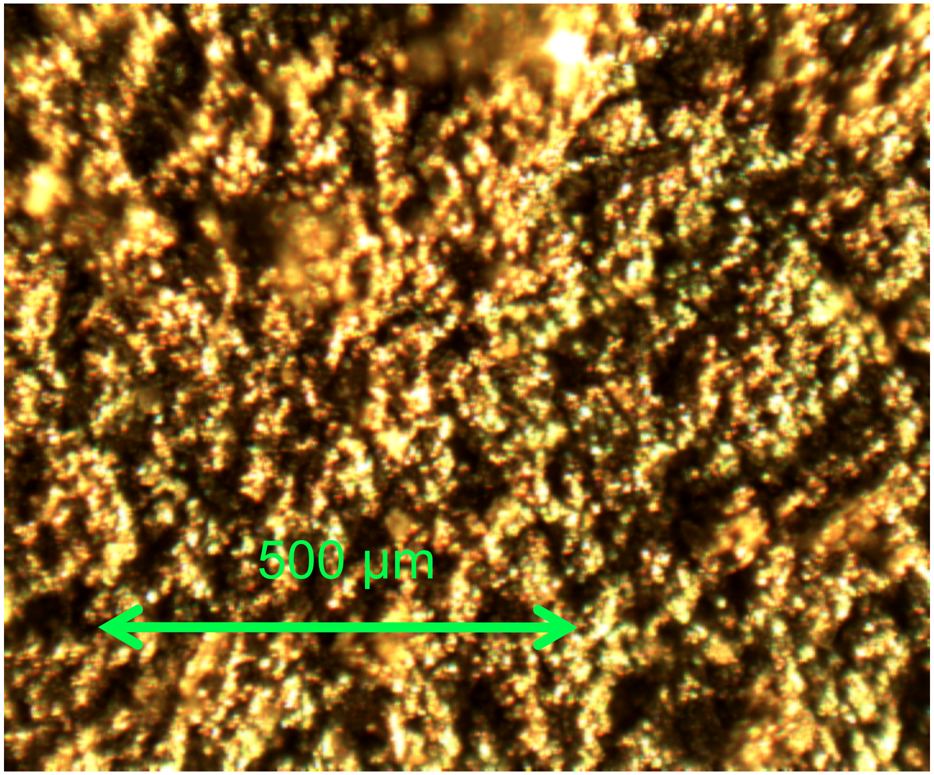
IR camera provides time-resolved 2D front face temperature data

- **Camera resolution:**
  - **~1mm spatial**
  - **33.3 ms temporal**
- **LLD sample "plunged" in front of neutral beam for 1-3 s**
  - **Power density ~1-2 MW/m^2**
- **Front face temperature recorded by IR camera**
  - **Absolute temperatures determined via calibration**
  - **Performed with replicated experimental conditions, matches TC data to within 10° C**
- **Back face temperature recorded by TCs**

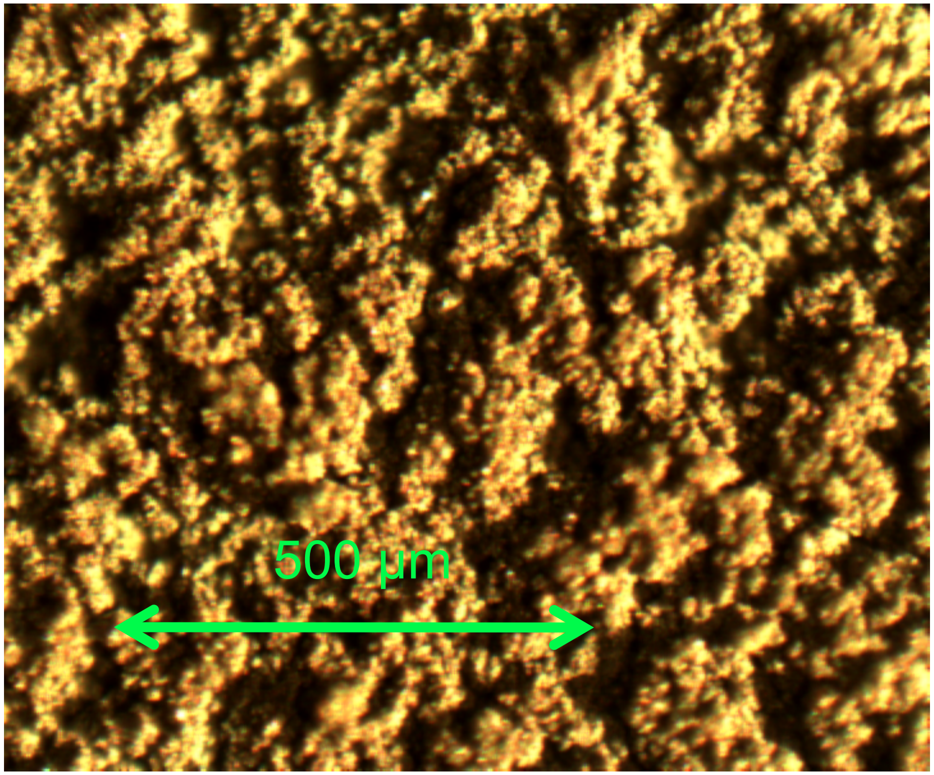


False color image of LLD sample during neutral beam exposure

Optical microscope initially used to study LLD sample surface with micron-level spatial resolution

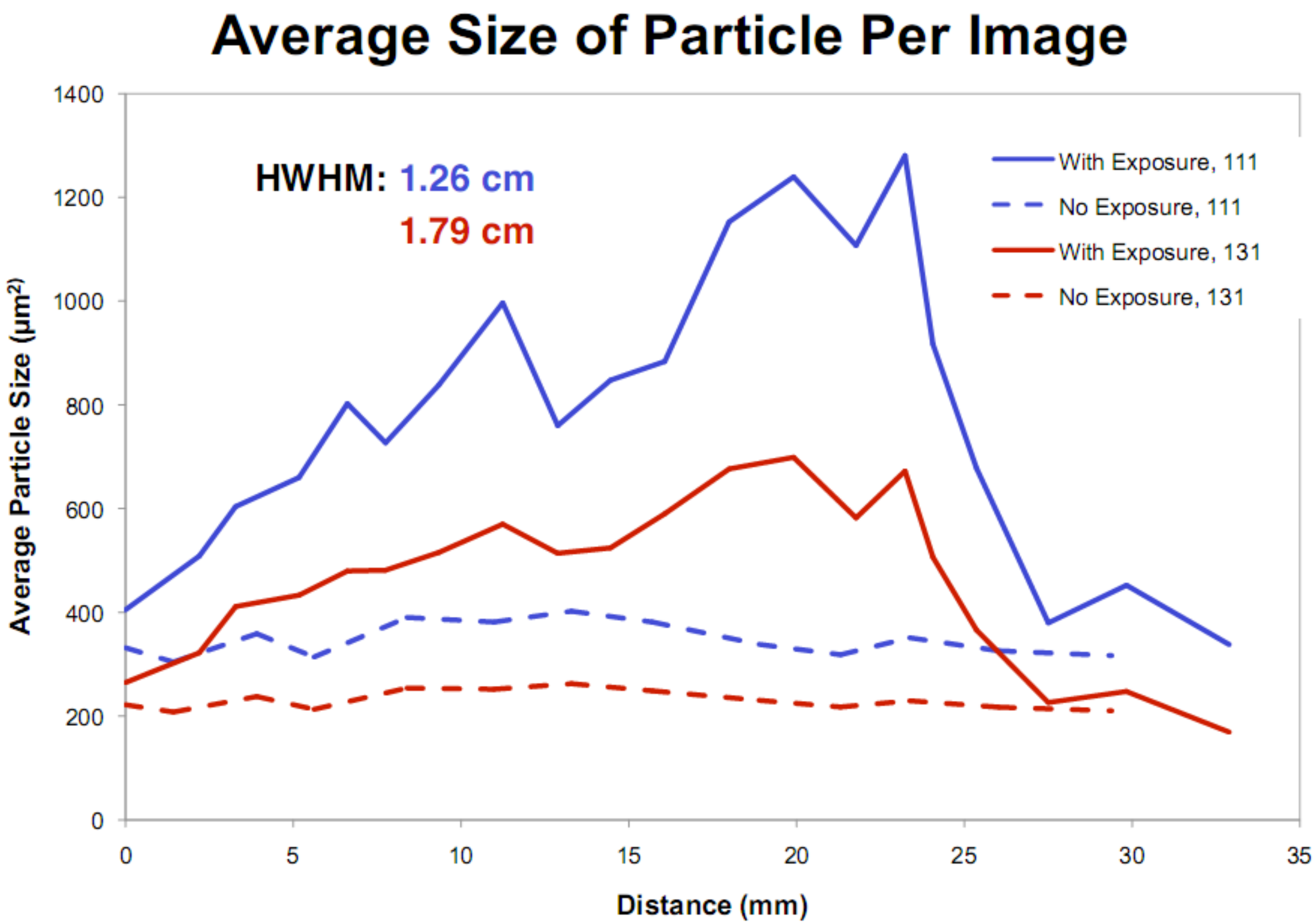


No Beam Exposure

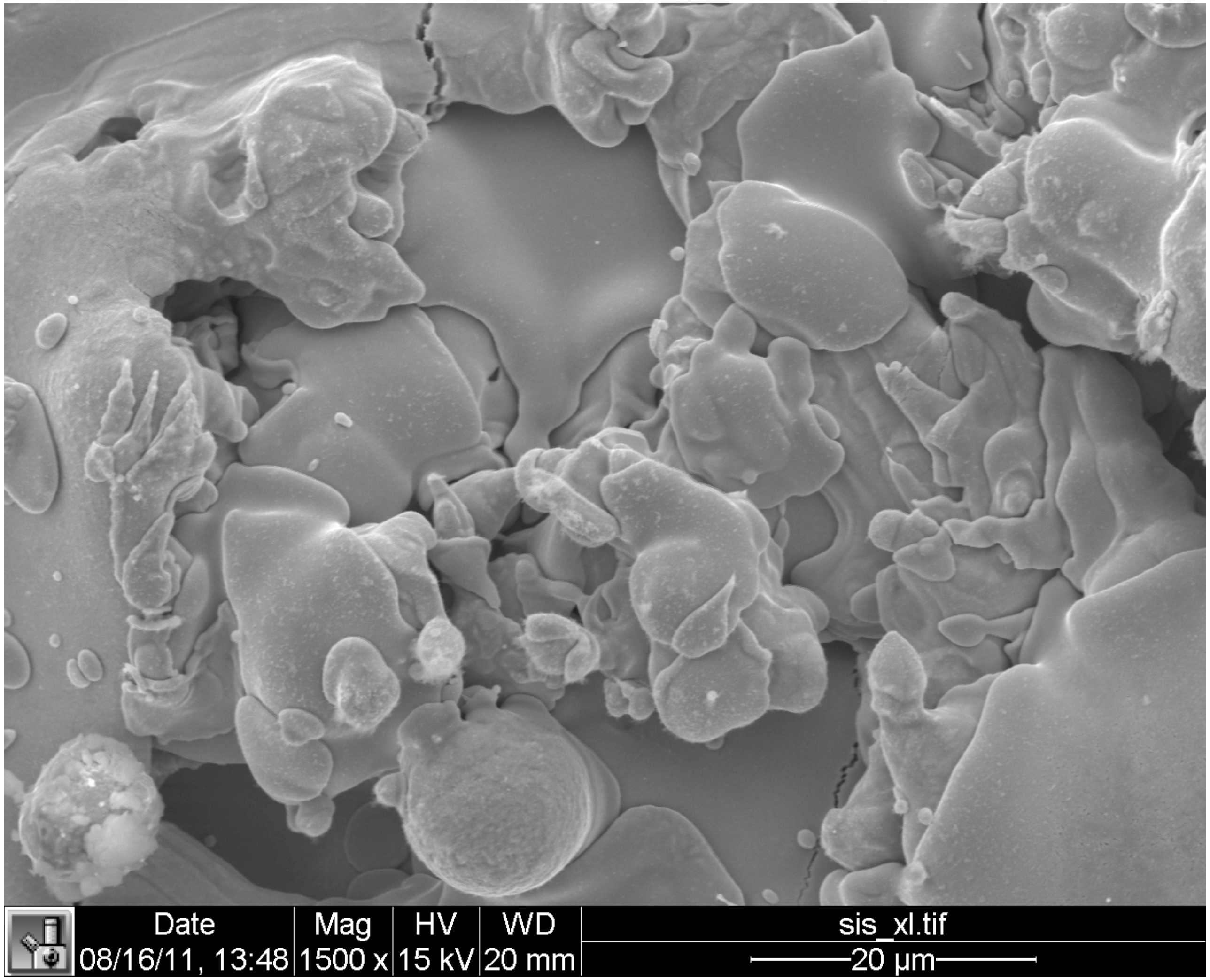


With Beam Exposure

Evidence for surface damage of sample from exposure to neutral beam observed

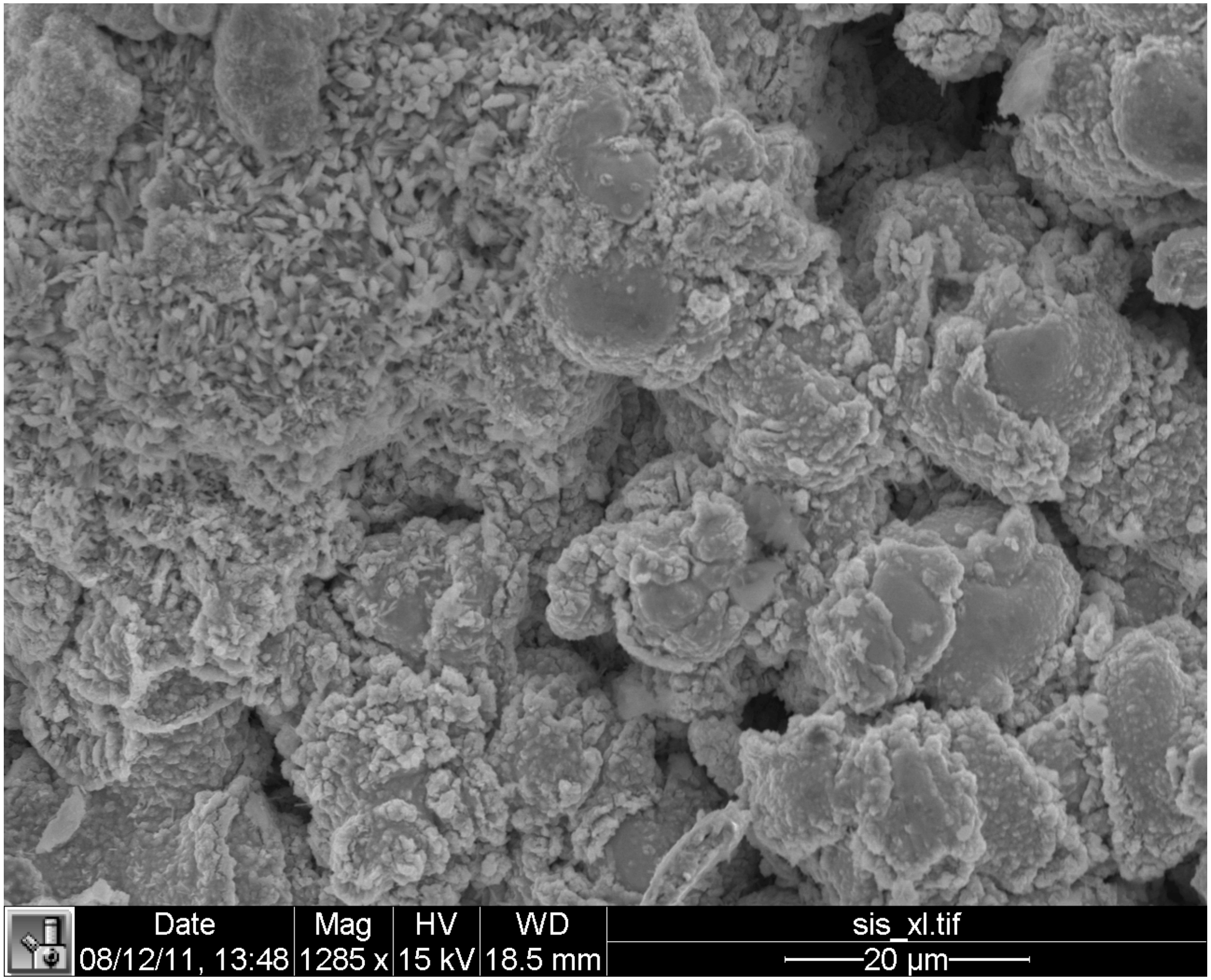


SEM image of unexposed LLD surface provides baseline surface characterization



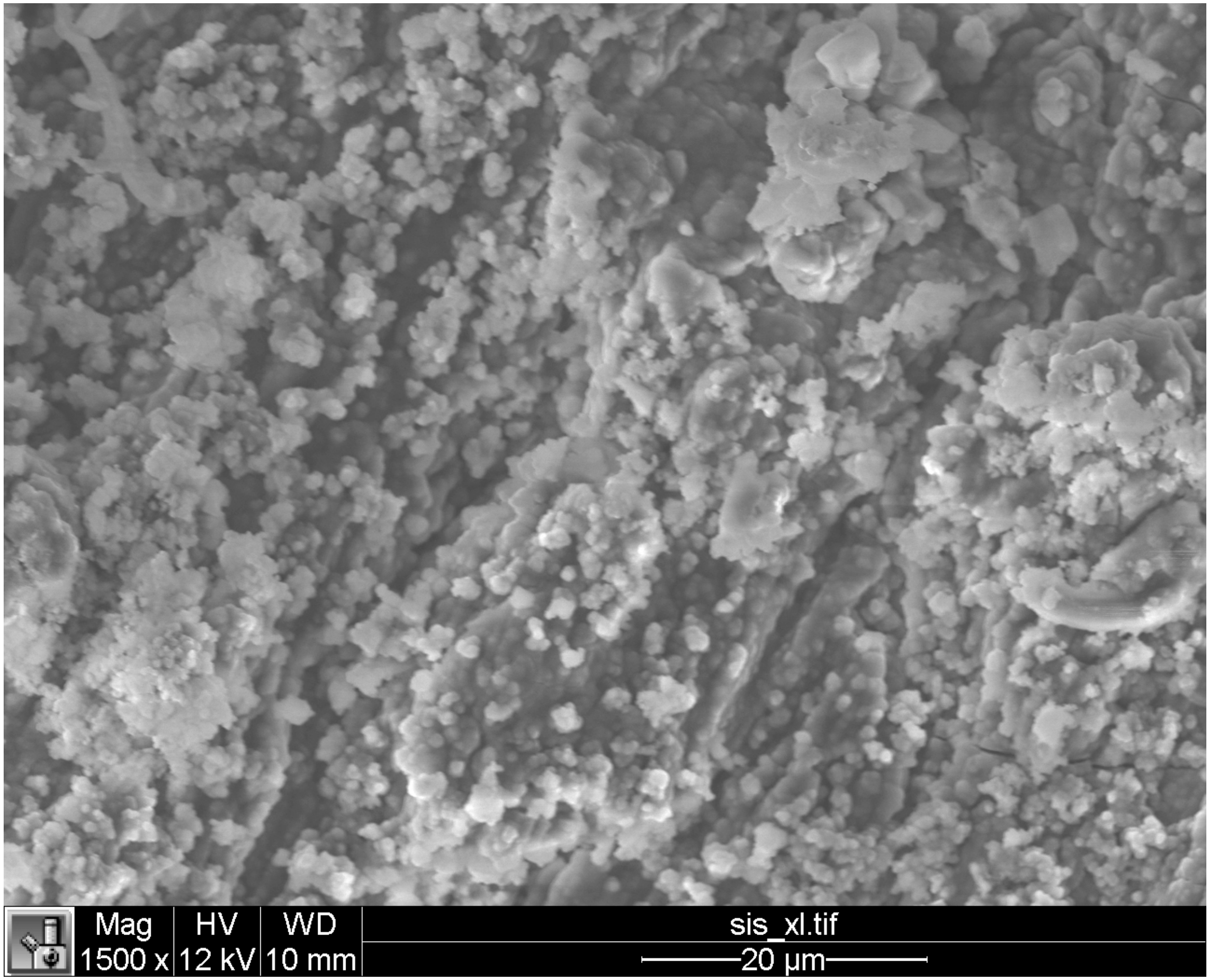
A. Khan, S. Bernasek, et al., Dept. of Chemistry, Princeton U.

LLD surface exposed to neutral beam shows small scale features that may affect larger structures



A. Khan, S. Bernasek, et al., Dept. of Chemistry, Princeton U.

Small scale structure predominates SEM image of LLD surface with lithium exposed to neutral beam



A. Khan, S. Bernasek, et al., Dept. of Chemistry, Princeton U.

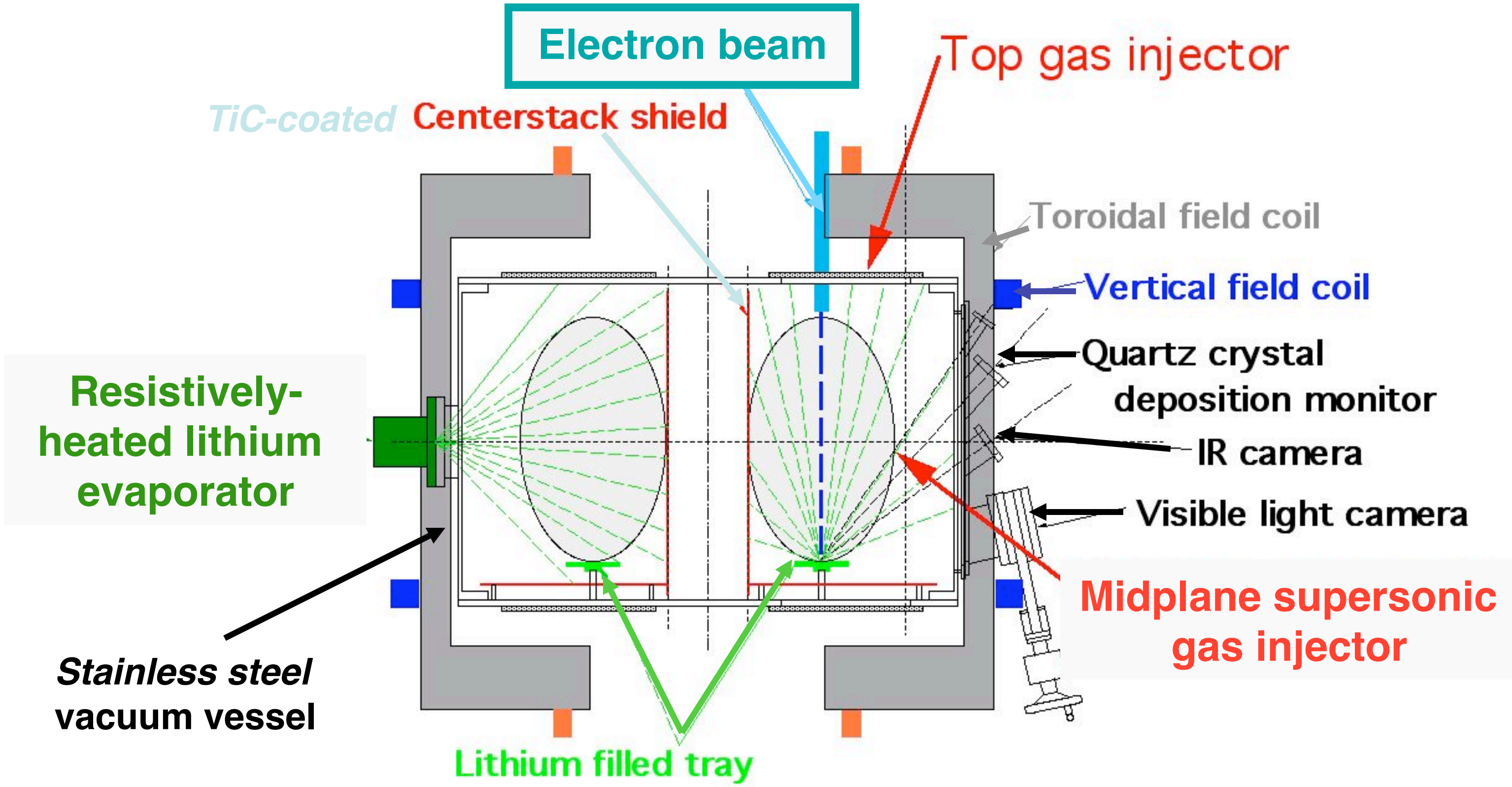
Surfaces similar for Liquid Lithium Divertor samples with and without lithium

- **Small-scale structure after beam exposure does not appear to be qualitatively different**
  - **Similar to solid materials exposed to ion bombardment in linear plasma devices**
  - **Coating may not have melted even if temperature rose well above 181°C melting point**
    - **Surface melting not observed during beam exposure**

Explanation could be in nature of coating on top of lithium in Liquid Lithium Divertor

- **"Front face" temperature of actual LLD and LLD sample never exceeded 462°C melting point of lithium hydroxide**
  - **LLD designed with thin stainless steel liner and "lithium bearing" plasma-sprayed molybdenum layer**
  - **Enabled temperature response to be governed by thermal mass of copper substrate**
- **Results consistent with electron beam heating of Current Drive Experiment-Upgrade (CDX-U) tray limiter**
  - **Lithium motion first observed *beneath* surface layer**

Electron beam installed on CDX-U* initially for as method to create lithium-coated PFC's

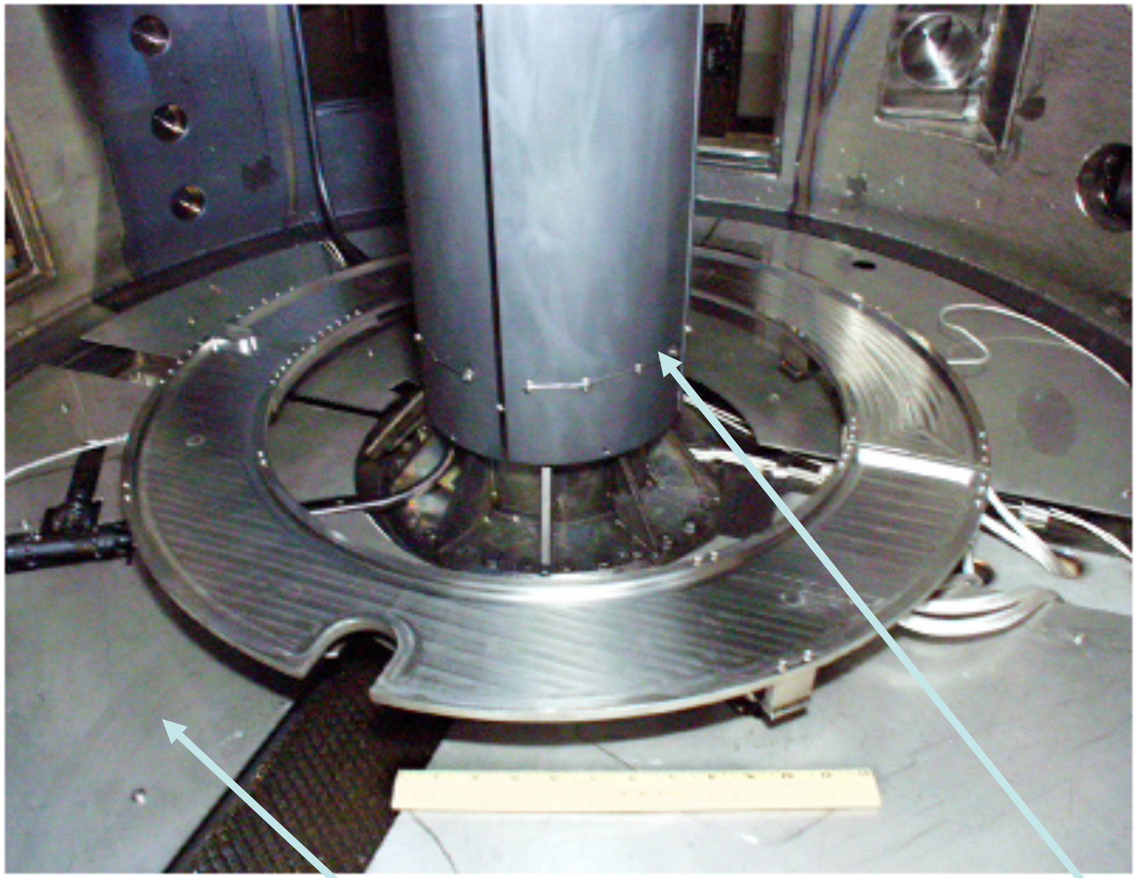


Fully toroidal tray: R_0= 34 cm,
width = 10 cm, 6 mm deep

- "Tray" only provides "partial" liquid lithium PFC
- Resistively-heated evaporator and electron beam heating lithium in tray provide greater PFC coverage

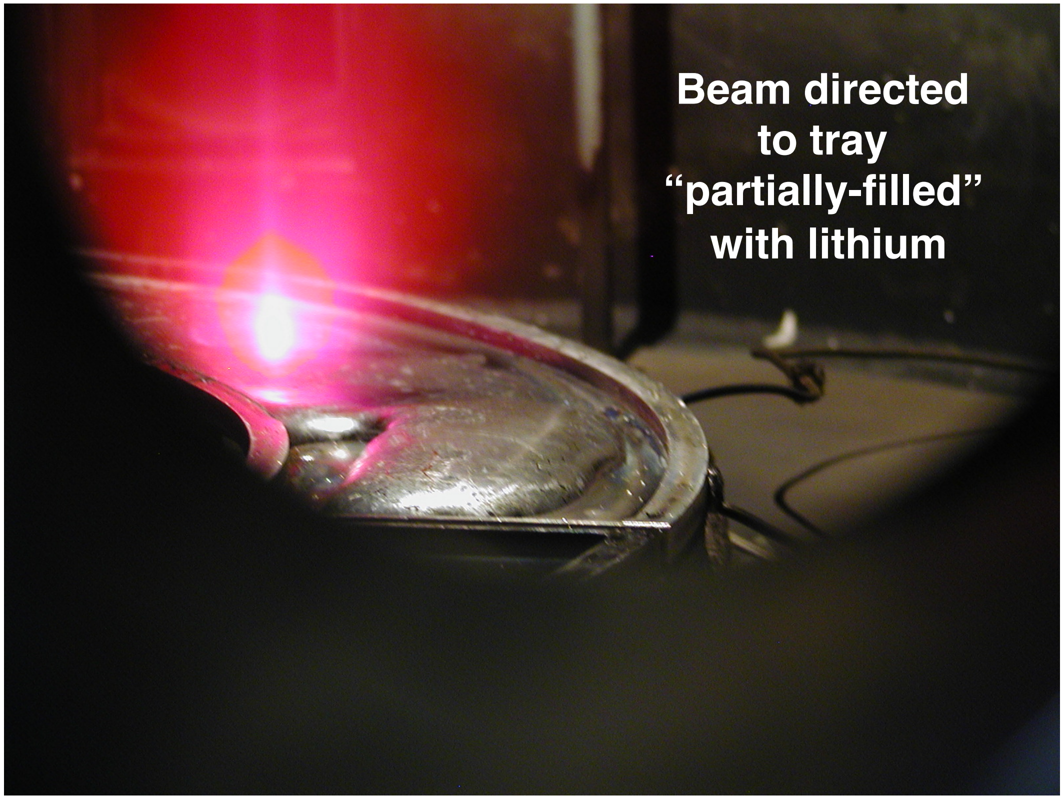
**R. Majeski et al., PRL 97, 075002 (2006); R. Kaita et al., Phys. Plasmas 14, 056111 (2007)*

Stainless steel "tray" used to hold liquid lithium in CDX-U



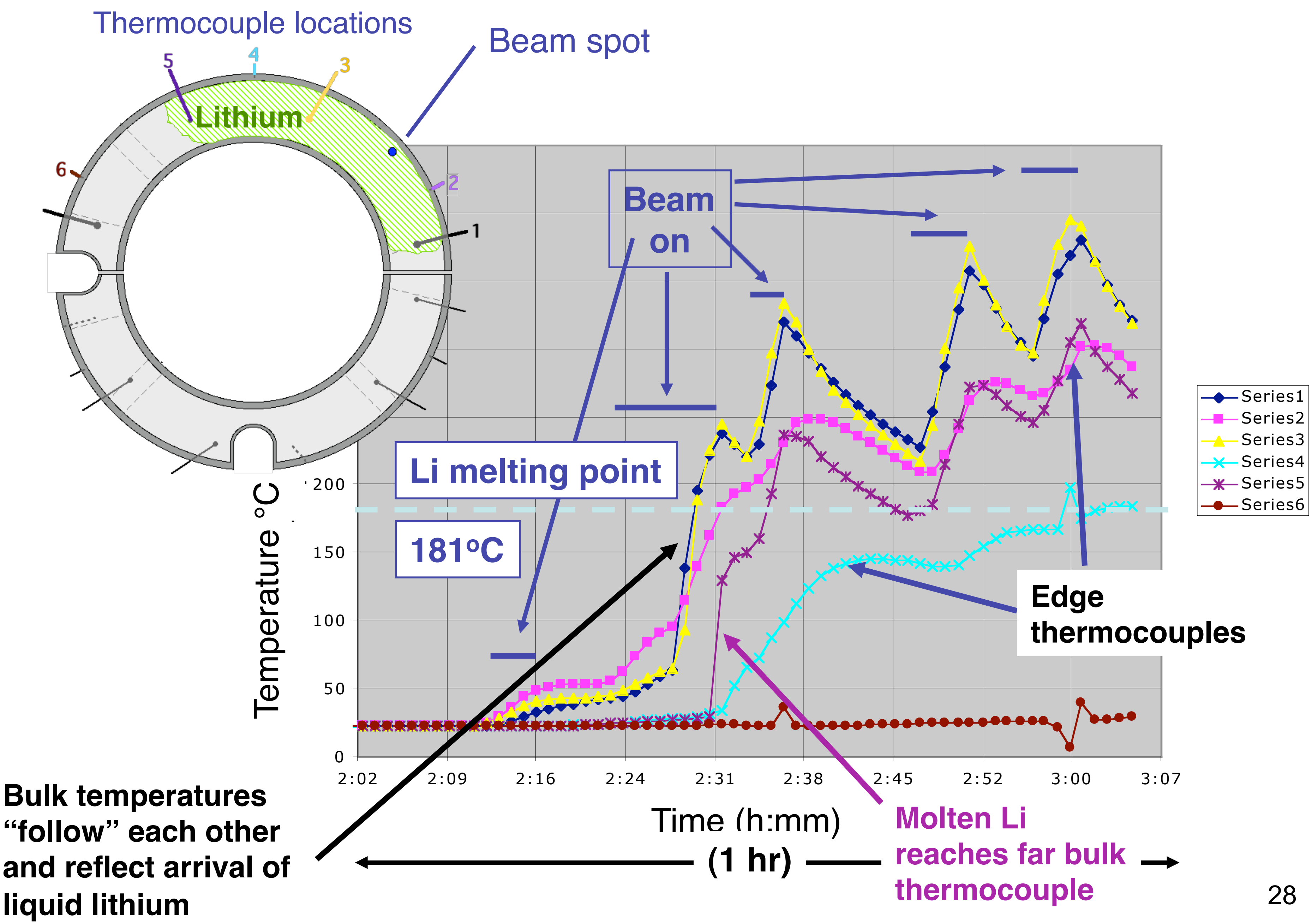
- 34 cm major radius, 10 cm wide, 0.64 cm deep
- Fabricated in two halves with a toroidal electrical break
- Heaters beneath for temperature control up to 500°C
- Heat/lithium shield between tray and lower vacuum flange
- Heat shield on center stack

CDX-U poloidal field coils used to provide vertical "guide" field to direct e-beam to lithium



- **100 nm lithium wall coatings at maximum evaporation rate of 600 mg/minute**
  - **CDX-U magnetic fields guide 4 kV, 0.3 - 0.4 A beam for 300 - 400 seconds**
  - **Lithium area in tray ~600 cm^2 >> beam spot for power density up to 60 MW/m^2**

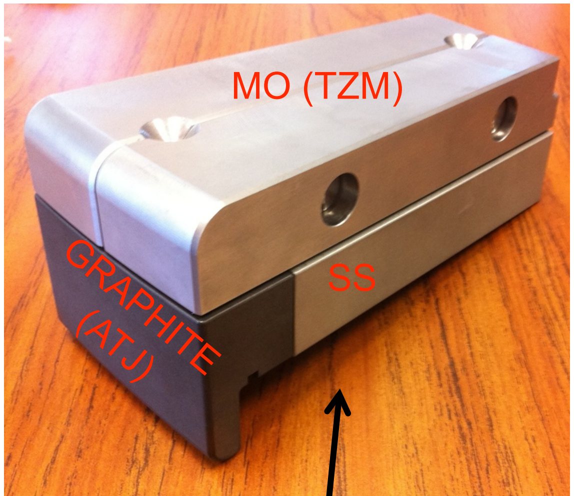
All Li in CDX-U tray liquefied prior to evaporation



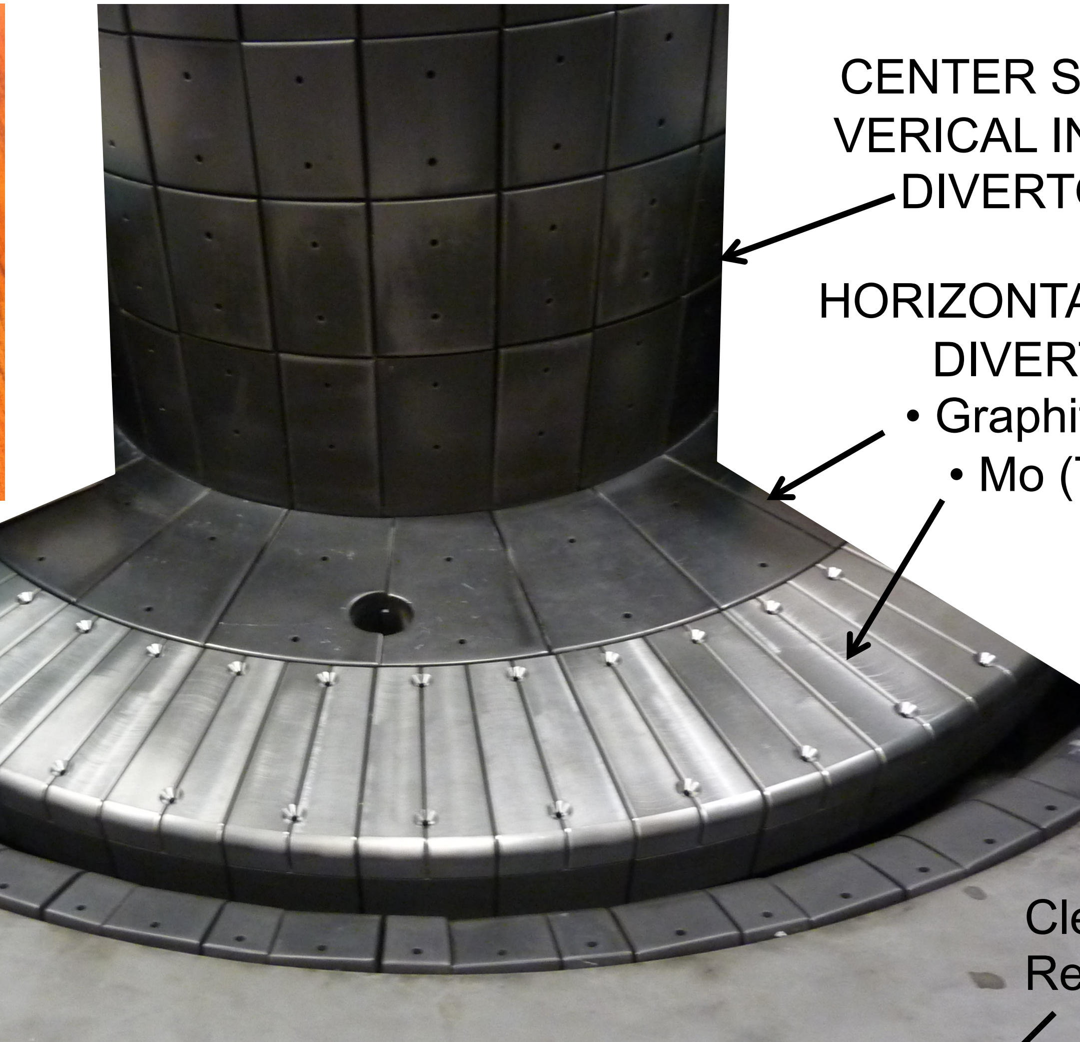
Results indicate that *flow* is necessary if liquid lithium divertor is installed on NSTX upgrade

- LLD still validated basic design of substrate for lithium
  - Absence of macroscopic damage to LLD surface
  - Absence of molybdenum and iron in plasma
- Molybdenum tiles under consideration as plasma-facing components for NSTX upgrade
  - To be coated by lithium from LITER evaporators
  - Intermediate step between solid carbon and flowing liquid lithium

Mo installed on inner divertor in 2011 to determine relationship between strikepoint and C source



MOLYBDENUM TILE ASSEMBLY



CENTER STACK VERICAL INNER DIVERTOR

HORIZONTAL INNER DIVERTOR
- Graphite (ATJ)
- Mo (TZM)

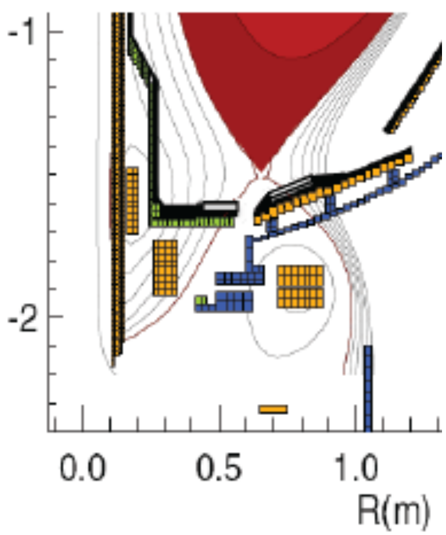
CHI GAP

LLD Cleaned & Reinstalled

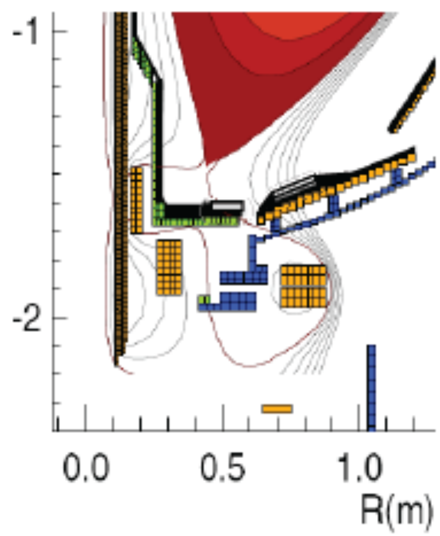
- Both inner and outer strike points can be placed on Mo
- Vary divertor carbon sputtering source term by moving discharge

Experiments can be conducted with strike points on combination of Mo and C surfaces

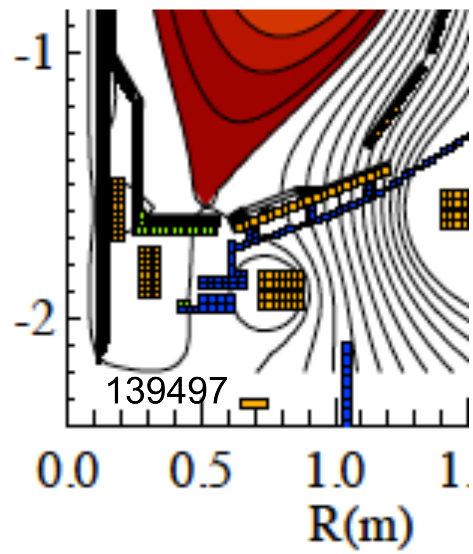
1. Mo-LLD and Mo tile strikepoints



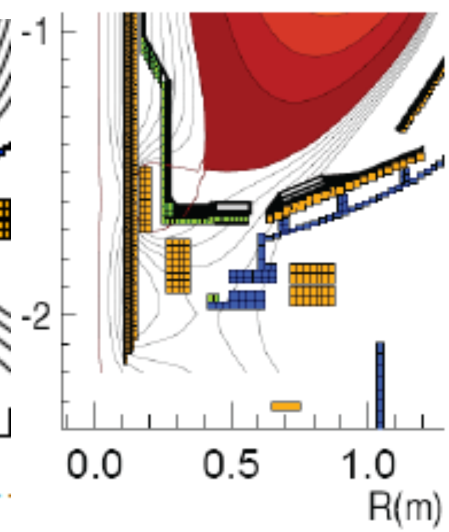
2. Mo-tile outer strikepoint and C inner strikepoint



3. “Snowflake” with inner strikepoint on Mo (V.Soukhanovskii)



4. Both strikepoints on C



Questions to be addressed with C inboard and outboard divertor tiles and Mo inboard divertor tiles and Mo LLD surface:

How does core C^{6+} change?

How does core D^{+} change?

How does electron density rise change?

How does edge C source term change, Prad?

How do edge conditions (ELMs, quiesence) change?

Summary and Conclusions

- LLD operation successfully demonstrated with strike point on lithium-filled surface (required for NSTX-U to have full power, long pulse Li PFC conditions)
  - Thermal response during discharge dominated by thermal mass of the copper
  - No macroscopic evidence of surface damage by lithium or heating

- Sufficient lithium was deposited for first time at fast enough rate to maintain good plasma performance without He GDC between discharges
  - About 30 plasmas on LLD were followed by around 150 plasmas on lithiated graphite

- LLD in its effect on plasma performance did not clearly differ from evaporative lithium coatings
  - LLD temperatures exceeded melting point of lithium but lithium compounds from impurities may have remained undissolved on surface
  - Earlier electron beam and more recent neutral beam experiments have shown that lithium can liquefy beneath impurity coatings

- Issues of lithium vacuum chemistry need investigation to interpret static liquid lithium results and develop design of flowing lithium system for NSTX-U.